

Hydrogen-poor super-luminous stellar explosions

R. M. Quimby, S. R. Kulkarni, M. M. Kasliwal,

Cahill Center for Astrophysics 249-17, California Institute of Technology, Pasadena, CA 91125, USA,

A. Gal-Yam, I. Arcavi,

Ben-Zvi Center for Astrophysics, Faculty of Physics, Weizmann Institute of Science, 76100 Rehovot, Israel,

M. Sullivan,

Department of Physics (Astrophysics), University of Oxford, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH,

UK,

P. Nugent, R. Thomas,

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA,

D. A. Howell,

Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Goleta, CA 93117, USA,

Department of Physics, University of California, Santa Barbara, Broida Hall, Santa Barbara, CA 93106, USA,

E. Nakar,

Raymond and Beverly Sackler School of Physics & Astronomy, Tel Aviv University, Tel Aviv 69978, Israel,

L. Bildsten,

Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Goleta, CA 93117, USA,

Kavli Institute for Theoretical Physics, Kohn Hall, University of California, Santa Barbara, CA 93106, USA,

C. Theissen,

University of California, San Diego, Department of Physics, 9500 Gilman Drive, La Jolla, CA 92093, USA,

N. M. Law,

Cahill Center for Astrophysics 249-17, California Institute of Technology, Pasadena, CA 91125, USA,

Dunlap Institute for Astronomy and Astrophysics, University of Toronto, 50 St. George Street, Toronto Ontario, Canada,

M5S 3H4,

R. Dekany, G. Rahmer, D. Hale, R. Smith,

Caltech Optical Observatories, California Institute of Technology, Pasadena, CA 91125, USA,

E. O. Ofek,

Cahill Center for Astrophysics 249-17, California Institute of Technology, Pasadena, CA 91125, USA,

J. Zolkower, V. Velur, R. Walters, J. Henning, K. Bui, D. McKenna,

Caltech Optical Observatories, California Institute of Technology, Pasadena, CA 91125, USA,

D. Poznanski,

Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA,

Astronomy Department, University of California, Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA,

Einstein Fellow,

S. B. Cenko,

Astronomy Department, University of California, Berkeley, 601 Campbell Hall, Berkeley, CA 94720, USA,

D. Levitan,

Department of Physics, California Institute of Technology, Pasadena, CA 91125, USA

Supernovae (SNe) are stellar explosions driven by gravitational or thermonuclear energy, observed as electromagnetic radiation emitted over weeks or more[1]. In all known SNe, this radiation comes from internal energy deposited in the outflowing ejecta by either radioactive decay of freshly-synthesized elements[2] (typically ^{56}Ni), stored heat deposited by the explosion shock in the envelope of a supergiant star[3], or interaction between the SN debris and slowly-moving, hydrogen-rich circumstellar material[4]. Here we report on a new class of luminous SNe whose observed properties cannot be explained by any of these known processes. These include four new SNe we have discovered, and two previously unexplained events[5, 6] (SN 2005ap; SCP 06F6) that we can now identify as members. These SNe are all ~ 10 times brighter than SNe Ia, do not show any trace of hydrogen, emit significant ultra-violet (UV) flux for extended periods of time, and have late-time decay rates which are inconsistent with radioactivity. Our data require that the observed radiation is emitted by hydrogen-free material distributed over a large radius ($\sim 10^{15}$ cm) and expanding at high velocities ($> 10^4 \text{ km}^{-1} \text{ s}^{-1}$). These long-lived, UV-luminous events can be observed out to redshifts $z > 4$ and offer an excellent opportunity to study star formation in, and the inter-

stellar medium of, primitive distant galaxies.

The Palomar Transient Factory (PTF)[7, 8] is a project dedicated to finding explosive events and has so far identified over a thousand SNe. PTF09atu, PTF09cnd, and PTF09cwl (also SN 2009jh[9]) were detected by the 1.2 m Samuel Oschin Telescope during commissioning of the PTF system, and PTF10cwr[10, 11, 12] (also SN 2010gx[13]) was detected the following year (Figure 1; see Supplementary Information [SI] § 1). As with other SN candidates, optical spectra for classification were obtained by the 10 m Keck I, 5.1 m Palomar, and 4.2 m William Herschel telescopes. The spectra (Figure 2) show broad absorption dips at short wavelengths and mostly smooth continua to the red thereof. We further identify narrow absorption features in the PTF spectra from the Mg II $\lambda\lambda 2796, 2803$ doublet, and measure redshifts of $z = 0.501, 0.258, 0.349$, and 0.230 for PTF09atu, PTF09cnd, PTF09cwl, and PTF10cwr, respectively. After combining the three available spectra of the SCP 06F6 transient, we find the data correlate to the PTF sample and may also show narrow Mg II absorption redshifted by $z = 1.189$ (SI § 4). Similarly to all PTF events, SN 2005ap ($z = 0.283$) shows a distinct “W” absorption feature near rest wavelength 4300 \AA . Although the broad spectral features of SN 2005ap are systematically shifted to higher velocities, the over-all resemblance is striking. The PTF discoveries bridge the redshift gap between SCP 06F6 and SN 2005ap and link these once disparate events, thus unifying them all into a single class.

With the redshifts above and standard $H_0 = 71$, $\Omega_m = 0.27$ flat cosmology, the peak absolute u -band AB magnitudes[14] for the PTF transients in the rest frame are near -22 , and -22.3 for SCP 06F6 (Figure. 3). The ~ 50 day rise of SCP 06F6 to maximum in the rest frame is compatible with the PTF sample, although there appears to be some diversity in the rise and decline timescales. To power these high peak magnitudes with radioactivity, several solar masses of ^{56}Ni are needed ($> 10 M_\odot$, e.g., ref. [15]), and yet in the rest frame V -band, the post-maximum decline rates of the PTF events are all $> 0.03 \text{ mag day}^{-1}$, which is a few times faster than the decay rate of ^{56}Co (the long-lived daughter nucleus of ^{56}Ni). These are therefore not radioactively-powered events.

Next we check if the observed photons could have been deposited by the explosion shock as it traversed the progenitor star. The photospheric radius R_{ph} we infer for PTF09cnd at peak luminosity, based on the observed temperature and assuming black-body emission, is $R_{ph} \sim 5 \times 10^{15}$ cm (SI Figure S1). If the radiated photons were generated during the star explosion, then adiabatic losses imply that only a fraction R_*/R_{ph} of the energy remains in the radiation at any given time where R_* is the initial stellar radius. Given that the energy radiated around the peak is $\sim 10^{51}$ erg and that for any reasonable hydrogen-stripped progenitor $R_*/R_{ph} < 10^{-3}$, this model requires an unrealistic total explosion energy of $> 10^{54}$ erg. In fact the large radius and the duration of PTF09cnd leave almost no place for adiabatic losses (SI § 5), implying that the internal energy must have been deposited at a radius that is not much smaller than R_{ph} .

Integrating the rest frame g -band light curve and assuming no bolometric correction, we find that PTF09cnd radiated $\sim 1.2 \times 10^{51}$ erg. A similar analysis of the SCP 06F6 data gives a radiated energy of $\sim 1.7 \times 10^{51}$ erg. We also fit Planck functions to the UV and optical observations of PTF09cnd (SI Figure S1) and find an approximate bolometric output of $\sim 1.7 \times 10^{51}$ erg. The derived black body radii indicate a photospheric expansion of $v_{phot} \sim 14,000$ km s $^{-1}$. If the main source of luminance is the conversion of kinetic energy, then the bolometric energy would require $\sim 1 M_{\odot}$ of material at this velocity, assuming a conversion efficiency of 100%. A more realistic efficiency factor would make the minimum mass a few times larger. Since no traces of hydrogen are seen in any of the spectra (SI § 3), interaction with regular H-rich CSM is ruled out. We thus conclude that these events cannot be powered by any of the commonly invoked processes driving known supernova classes.

The early spectra presented here are dominated by oxygen lines, and do not show calcium, iron, or other features commonly seen in regular core-collapse SNe. The lack of metals is particularly noticeable in the UV flux, which is typically depleted by absorption. These events are hosted by low-luminosity galaxies that may provide a sub-solar progenitor environment (SI § 6). The new class of events we identified is thus observationally

characterized by extreme peak luminosities, rapid decay times inconsistent with radioactivity, very hot early spectra with significant UV flux, and lacking absorption lines from heavy elements like calcium and iron commonly seen in all other types of SNe.

These observations require a late deposition of a large amount of energy ($> 10^{51}$ erg) into hydrogen-poor, fast-expanding material (slow moving material would produce narrow spectroscopic features, which are not observed). We point out two possible physical processes that can perhaps power these super-luminous sources. One is a strong interaction with a massive, rapidly-expanding, hydrogen-free shell or wind. Such a scenario is naturally produced by extremely massive stars with initial masses in the range $90 M_{\odot} \lesssim M_i \lesssim 130 M_{\odot}$, which are expected [16, 17] to undergo violent pulsations, perhaps driven by the pair-instability, stripping their outer layers and expelling massive H-poor shells. The star eventually dies through a stripped-envelope, core-collapse supernova, which may interact with previously ejected C/O-rich shells to drive the observed luminosity [18]. Alternatively, the power source can be a prolonged energy injection by a central engine. For example, a spinning-down nascent magnetar [19, 20] can account for the peak luminosities ($> 10^{44} \text{ erg s}^{-1}$) and time to peak light (30-50 days) observed for these events, assuming a magnetic field $B \approx 1\text{-}3 \times 10^{14} \text{ G}$ and a natal spin of 1-3 ms.

The high luminosities, exceptionally blue spectral energy distributions, and rates (SI § 7) of this new class of supernovae make them prime targets for high redshift studies (SI Figure S3). Lingering around maximum light for months to years in the observer frame, these events provide a steady light source to illuminate their environs and any intervening clouds of gas and dust. This creates new opportunities for high resolution spectroscopy to probe distant star-forming regions in primitive galaxies, without the need for rapid scheduling, and with the benefit that the luminous SN beacon eventually fades, allowing to study the galaxy itself. Indeed these light houses mark a rich port for future thirty-meter-class-telescope science.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions R.M.Q. initiated, coordinated and managed the project, carried out photometric and spectroscopic observations and analysis, and wrote the manuscript. S.R.K is the PTF principal investigator and contributed to the manuscript preparation. M.M.K obtained spectroscopy from Keck and helped with the P60 observations. A.G.-Y. oversaw the Wise observations and contributed to analysis and manuscript writing. I.A. extracted the Wise photometry and helped obtain Keck spectra. M.S. carried out and analyzed spectroscopic observations from the WHT. P.N. designed and implemented the image subtraction pipeline that detected the PTF events. R.C.T. analyzed the combined spectra using his automated SYNOW code. D.A.Howell helped to identify the PTF spectra as SN 2005ap-like. E.N. contributed to the physical interpretation and manuscript

writing. L.B. advised during the preparation of the manuscript. C.T. helped vet potential candidates and first identified PTF09atu and PTF09cwl. N.M.L. is the PTF project scientist and oversaw the PTF system. R.D., G.R., D.H., R.S., E.O.O., J.Z., V.V., R.W., J.H., K.B., and D.McK. helped to build and commission the PTF system. D.P., S.B.C, and D.L. helped to vet PTF candidates and obtain spectroscopic observations.

Author Information Correspondence and requests for materials should be addressed to R.M.Q. (quimby@astro.caltech.edu).

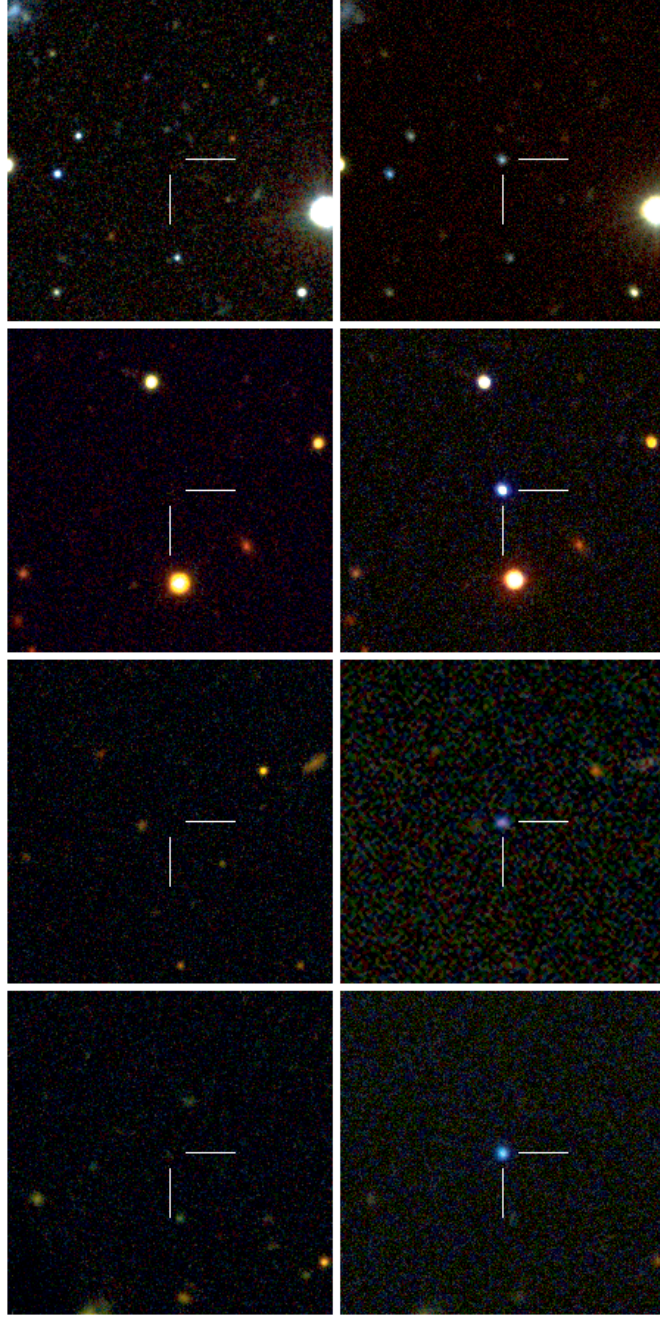


Figure 1: Before and after images of the UV luminous transients discovered by the Palomar Transient Factory. Top to bottom: PTF09atu, PTF09cnd, PTF09cwl, PTF10cwr. Each tile shows a false color image constructed by assigning image data from three separate band passes to red, blue, and green (g , r , and i -bands, respectively for PTF09atu; u , g or V , and r -bands for PTF09cnd, PTF09cwl, and PTF10cwr). In each case the SDSS reference data is shown to the left of the discovery follow-up frames, which are composed from Palomar 1.5 m, Wise 1.0 m and *Swift* UVOT observations.

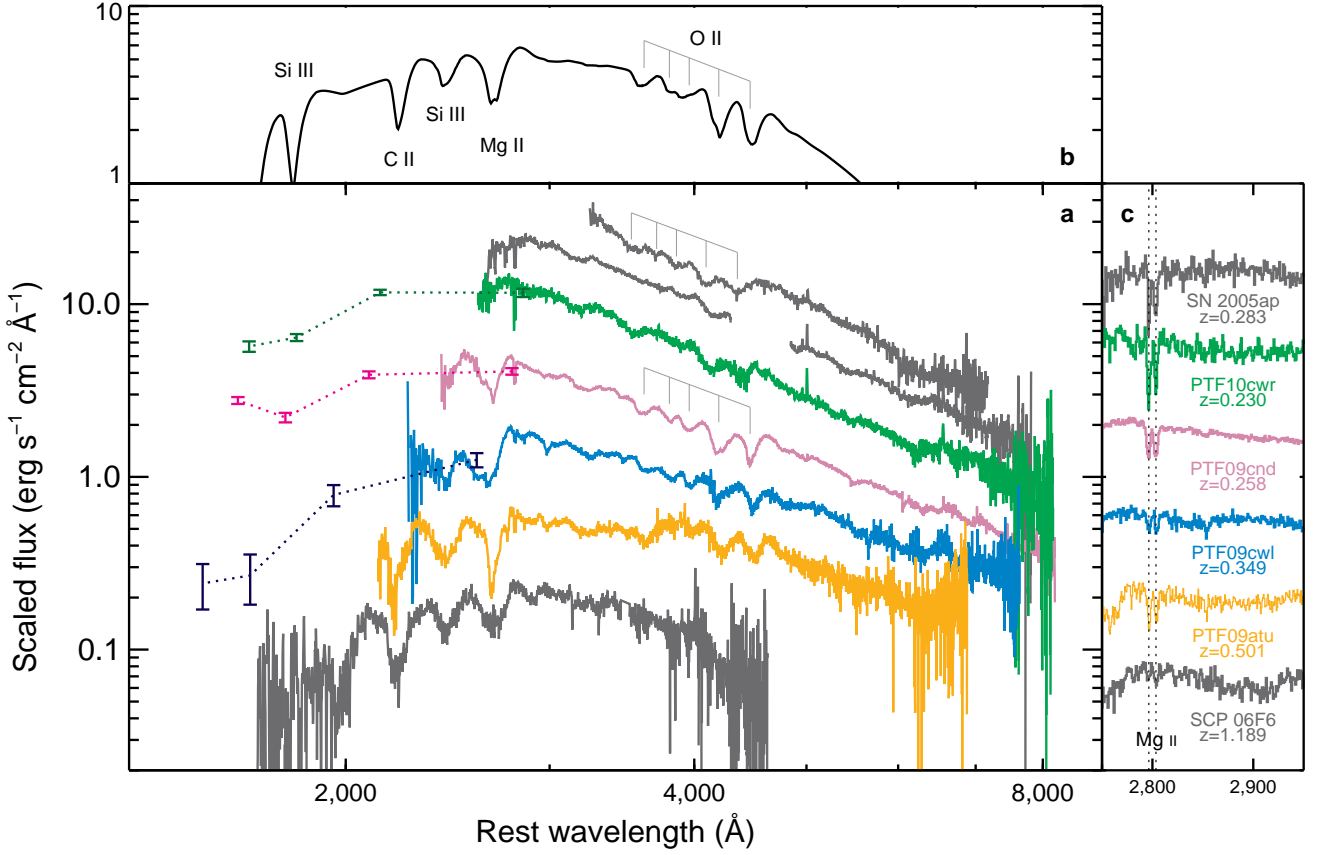


Figure 2: Spectral energy distributions of the 2005ap-like sample. **a**, Top to bottom: SN 2005ap on 2005 March 7 and again on March 16 (grey), PTF10cwr on 2010 March 18 (green), PTF09cnd on 2009 August 25 (purple), PTF09cwl on 2009 August 25 (blue), PTF09atu on 2009 July 20 (orange), and an average of all three SCP 06F6 spectra presented in ref. [6] (grey). The spectra have been de-redshifted, binned, and scaled arbitrarily for display purposes. Broad band flux densities from the *Swift* observations (scaled to join the spectra in the *u*-band) are plotted for PTF09cnd, PTF09cwl, and PTF10cwr with 1- σ error bars. Five absorption bands are marked by the combs above SN 2005ap and PTF09cnd, the former being $\approx 7,000$ km s⁻¹ faster. **b**, These features can be well fit by O II using the highly parametric spectral synthesis code, SYNOW[21] (see SI § 2). SYNOW fits also suggest that C II and Mg II can account for the 2200 Å and 2700 Å features, respectively. The fit to the 2500 Å line is improved with the addition of Si III. The model shown has a photospheric velocity of 15,000 km s⁻¹. **c**, Close-up views of the narrow Mg II doublet, from which we derive the redshifts.

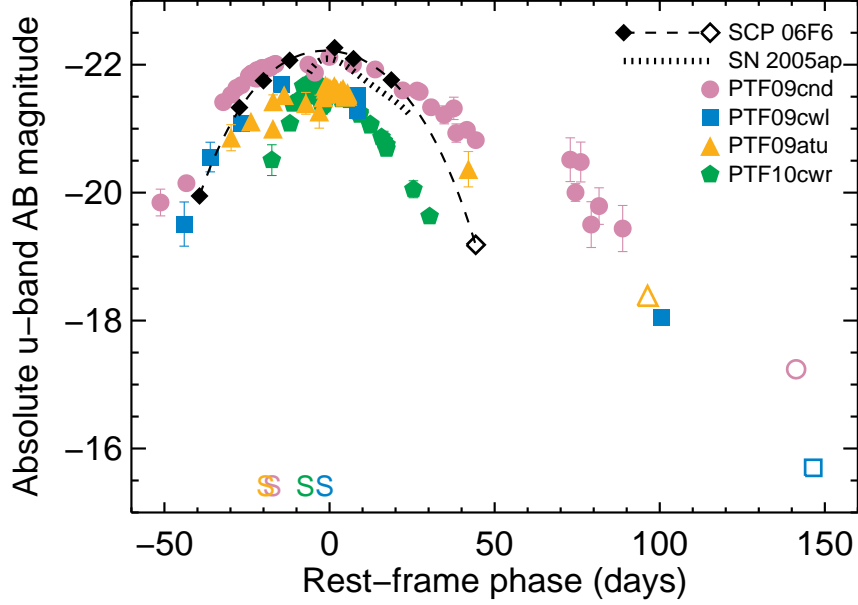


Figure 3: Luminosity evolution of the SN2005ap-like sample. Shown are the SCP 06F6 transient (diamonds), SN 2005ap (hash marks), PTF09atu (orange triangles), PTF09cnd (purple dots), PTF09cwl (blue squares), and PTF10cwr (green pentagons). In each case we transform the observed photometry to absolute u -band magnitudes by correcting both for distance and differences in the effective rest frame band pass introduced by the redshifts. For SCP 06F6, the observed i -band is similar to the rest frame u -band, so the correction factor is nearly independent from the spectral properties[22]. For the PTF sample, however, the correction factor varies over time as the spectra cool. We interpolated the observed spectra of PTF09cnd to phases appropriate for the B , g , V , and r -band observations of the PTF sample to calculate the correction factors. Statistical, 1σ errors (excluding the color correction) are shown when larger than the plotting symbols. The color corrections for PTF09atu and PTF09cwl near day 100 are very uncertain (~ 0.5 mag). We have not removed possible host light contaminating the late time observations of PTF09atu, PTF09cnd, and PTF09cwl (open symbols). Thus these measurements represent upper limits on the supernova light. Host galaxy light may in fact dominate the final PTF09cwl observation. The final observation of SCP 06F6 (open diamond) is a 2.5σ detection made from the ground. Along the abscissa we note the phases of the spectra shown in Figure 2 each with an “S.”